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ABSTRACT

Presented is a paper developed by the Learning Research and Development Center at the University of Pittsburgh and which is intended for science education researchers. Two major recommendations for the orientation of research in science education are proposed. The first is that currently espoused goals of science education should be reexamined and, if necessary, redefined. The second calls for science educators to become aware of and translate pertinent research methods, findings, and theories of behavioral scientists into appropriate instructional and research procedures for science education. The paper also applies the two recommendations as operating principles in both the development of instructional materials and in research design, providing an illustration for problem solving in both domains. (Author/HM)

LEARNING RESEARCH AND DEVELOPMENT CENTER

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Abstract

This paper proposes two major recommendations for the reorientation of research in science education. The first recommendation is that currently espoused goals of science education should be re-examined, and if necessary redefined. The second calls for science educators to become aware of and translate pertinent research methods, findings, and theories of behavioral scientists into appropriate instructional and research procedures for science education. The paper also applies the two recommendations as operating principles in both the development of instructional materials and in research design, providing an illustration for problem solving in both domains.

The primary audience for this paper is science education researchers. By heeding the recommendations set forth in this paper, science educators can potentially improve the quality of science education research and its influence on the teaching of science.

AN ORIENTATION FOR RESEARCH IN SCIENCE EDUCATION

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Thoughtful consideration of science education research reports suggests that there are serious deficiencies in how research in science education is conducted, reported, and communicated. The annual summaries of science education research that have been published in the past decade testify that the output of research reports is quite voluminous. The most recent summary to be published for the single year 1975 alone lists 379 items (Mallinson, 1977). However, the review of these 379 reports by Mallinson concludes with this comment:

> There is little wonder that research findings are not widely disseminated. Far too many reports are too difficult to read, and if deciphered, are found to deal with trivialities. (p. 230)

Similar sentiments about science education research have been voiced by othe knowledgeable persons. The majority of the research reported in the literature consists of isolated studies by individuals interested in a great diversity of questions. There are few long-term, focused efforts on particular problems by research groups or identifiable clusters of researchers. Science education research tends to be fragmented and noncumulative. Contributing to this situation is the fact that researchers in science education presently lack a sufficiently compelling theoretical framework or paradigm to guide their investigations (Lamb, 1976). Science education research typically is conducted with little or no awareness of pertinent paradigms and research procedures in relevant behavioral science disciplines. Moreover, despite a considerable flurry of research activity, hardly any generalizations from research findings can be made with confidence. Findings are communicated chiefly to other researchers, who are rarely in a position to influence classroom practice in science education. Little direct effort is expended by researchers to translate theory and research findings into classroom practice. When these translations are attempted, the processes used are usually ineffective, so that research seldom impacts classroom practice.

From all these considerations, it is clear that the productivity of science education has been much less than it might be and less than it ought to become. We believe that a new orientation is needed for research in science education to become more productive, both in developing a corpus of reliable knowledge about the phenomena investigated and in affecting the teaching of science in educational practice. These two important outcomes of science education research can be more fully realized when the research is conducted under the orientation suggested in this paper.

On the positive side, we recognize that the large volume of research reports generated by science educators is evidence of the science education community's commitment to research. We note, too, that the severest critics of the nature and quality of the research are included among the most respected members of the community. Moreover, science educators are actively involved at the national level in the process of setting policy that, in the long term, will positively influence research in science education.

The process of changing the orientation of research in science education will be slow and will require the concerted efforts of the whole science education community. Because we believe that individual researchers can go a long way in alleviating the shortcomings of science education research, we have chosen not to engage here in the debate over the policy issues involved. Rather, we propose two recommendations that can significantly reorient research in science education. We have found it useful to apply these recommendations as operating principles in conducting our research, and we believe they have significant implications for policy. When conscientiously heeded by individual researchers, the following recommendations have the potential for improving both the quality of science education research and its influence on the teaching of science.

Recommendation 1

The currently espoused goals of science education are in need of careful re-examination and analysis. The examination of an espoused goal should include, as a minimum, consideration of: (a) the evolution and tradition of the goal in science education; (b) current trends in public education and in the society that bear on the goal; and (c) recent developments relevant to the goal in the behavioral and natural sciences. When indicated by the analysis, the goal must be redefined to make it valid for contemporary science education.

Recommendation 2

Science educators [illegible] become cognizant of the current interests of behavioral scientis[illegible]s pertinent to particular problems and issues in science educa[illegible] also should take the responsibility for translating the research [illegible]ds, findings, and theories of behavioral scientists into appropriate instructional and research procedures for science education. Translation of pertinent results of basic psychological, sociological, and anthropological research into educational practice should be a designated priority for science education researchers.

We do not choose to argue for these recommendations on theoretical grounds in this paper. Rather, we think it is more valuable to illustrate their pragmatic virtues. To accomplish this, we shall discuss the application of the two recommendations in the context of research in problem solving in science education.

Problem Solving in Science Education

Science educators are nearly unanimous in professing the belief that problem solving and reflective thinking are important in children's learning of science in school. They advocate both the development of problem-solving skills as an outcome of science instruction and the use of problem-solving methods in instruction whenever appropriate. However, observations of science teaching in elementary and secondary school classrooms usually reveal that opportunities for students to engage in reflective thinking are all too rare. The methods so frequently recommended by science educators are not often found in actual instructional practice in schools, so that the desired outcome of developing problem-solving skills is rarely achieved.

The obvious disparity between science educators' oft-voiced recommendations and what actually transpires in science education concerning problem solving and reflective thinking is embarrassing. More than that, when dictate and practice are so much out of joint, it is a sure sign that something serious is amiss. Identifying where the difficulty lies is an urgent matter for science education; only when this is known can proper remedies be fashioned. We suggest that science education research can help both to identify the difficulty and to fashion remedies if researchers will attend to the two recommendations we have proposed. Most of the remainder of this paper illustrates how this can be done.

Examination of the Problem-Solving Goal

According to our own first recommendation for the reorientation of research in science education, the currently espoused goals of science education are in need of re-examination and analysis. Thus, in the present instance, an examination of problem solving as a goal in science education is called for. The examination of this goal should specifically consider: (a) the history of problem solving in science education, (b) current trends in public education that bear on the goal, and (c) recent developments in behavioral and natural sciences that are relevant to the goal.

Some important developments in cognitive psychology are the most relevant to the examination of the problem-solving goal. A great deal of research activity on problem solving by various cognitive psychologists has produced theoretical and empirical results that are pertinent to this goal in science education. However, as our second recommendation emphasizes, appropriate translations of psychological research procedures and results must be made before they can properly be applied in science education. For this reason, we shall discuss the developments in cognitive psychology that are pertinent to the goal later in this paper in the section dealing with our second recommendation. In the present section, we examine the goal in the light of the history of problem solving in science education and current trends in public educatio .

History of Problem Solving in Science Education

The history of problem solving in science education serves to illuminate the source and persistence of three pervasive and as yet unresolved issues requisite to the problem-solving goal of science education. These are: (a) consistent delineation of the development of problem-solving ability--a desired outcome or end--from utilizing problem-solving methods in instruction--a means to attain an end; (b) clear and complete definition of the meaning of the desired outcome of developing children's problem-solving ability; and (c) the extent to which it is reasonable to expect children to attain the outcome of developing problem-solving ability. To a significant extent, these three issues are interrelated, but each is worth considering in its own right.

Delineating outcome and methods. More than anyone else, John Dewey is responsible for the devotion of science educators to reflective thinking and problem solving. Because of Dewey's prestige as a philosopher and educator, his interest in the teaching of science was a boon to science education. On the other hand, the concern in his philosophy for obliterating the duality of ends and means becomes the source of considerable difficulty in delineating the problem-solving outcome from problem-solving methods in science teaching.

Significantly, the first article in the first volume of the journal, Science Education (which was then called General Science Quarterly), in 1916 was a contribution by Dewey entitled "Method in Science Teaching." At the outset of this article, Dewey is quite clear and succinct about his view of method.

> Method means a way to a result, a means to an end, a path to a goal. Method therefore varies with the end to be reached. Without a clear notion of the end, we cannot proceed intelligently upon the journey toward it. (p. 3)

He is equally clear about the outcome he advocates for science teaching.

> I say that the end of science teaching is to make us aware what constitutes the more effective use of mind, of intelligence. To give us a working sense of the real nature of knowledge, of sound knowledge as distinct from mere guess-work, opinion, dogmatic belief or whatever.
>
> Obviously science is not only knowledge, but it is knowledge at its best, knowledge in its tested and surest form. Educationally then what differentiates its value from that of other knowledge is precisely this superior quality. Unless it is taught that students acquire a realizing sense of what gives it its superiority, something is lost. (p. 3)

Consistent with his philosophy, Dewey seeks to obliterate the duality of means and ends and thus asserts that it is "important to see to it that methods of teaching [science] are such as to fulfill its true purpose" (1916, p. 4). Dewey states unequivocally that elementary education is important in the process of educating reflective thinkers, and he discusses briefly the methods he believes appropriate. He urges that science teaching should be dynamic, truly scientific, because "the understanding of process is at the heart of scientific attitude" (p. 7). Being derived as it is from the very method of the natural sciences, Dewey's philosophy of science education was historically, as it is today, most appealing to science educators. Virtually all accept the central ideas of Dewey's philosophy. However, efforts to translate this philosophy into methods of classroom practice that can be readily communicated to teachers have been far from successful. This is due in part to the very nature of the philosophy. Dewey's intent to obliterate the means-end dualism and his view of intellectual activity as an integrated whole resulted in a philosophy that obstructs the kind of analysis necessary to translate it into functional methods and outcomes.

The difficulty which science educators evidence even today of consistently delineating the ends and means of science instruction can be traced, in part, to Dewey's philosophy. Those who followed Dewey attempted to adhere faithfully to the precepts of his philosophy, including the obliteration of the means-ends dualism. This philosophical position certainly has merit, but it is not free from potential confusion in practical applications. We observe all too often that, with respect to the problem-solving goal, incongruities exist between what science educators say they want to teach, what they actually teach, and what they test for after instruction.

An educator whose aim for instruction is to help students become more proficient problem solvers, who gives students opportunities to solve problems, and who then tests the students' capabilities as problem solvers is being consistent with Dewey's philosophy. In addition, this educator's aim, instructional method, and assessment procedure are consistent. If, however, the professed aim is for students to become better problem solvers, the method of instruction is lecture-demonstration, and the assessment procedure taps only recall of information, the educator is neither being consistent with Dewey's philosophy, nor are the educator's aim, instructional method, and assessment procedure consistent. We believe that inconsistencies of this type are attributable (a) to the confusions which arose when science educators sought to make practical applications of Dewey's philosophy, and (b) to the fact that, despite extensive efforts of a number of conscientious persons, there is no clear, complete definition of the meaning of problem solving in the context of science education. And yet, such a definition is prerequisite to implementing problem-solving instruction in science classrooms.

Defining problem-solving ability. It is much easier to assert that developing children's problem-solving ability is a worthy outcome of science instruction than it is to describe what this ability involves--not that science educators haven't tried. They have long recognized that defining the component elements of what came to be called the "problem-solving objective" is an essential task to accomplish. Definitions of the component elements are necessary for assessing student performance and for planning instruction. There is a good deal of confusion and inconsistency in the use of terminology surrounding the definition of problem-solving ability. In addition to the term, "problem-solving objective," terms frequently used in the science education literature include scientific method, scientific thinking, critical thinking, method of intelligence, inquiry skills, and processes. Though some distinctions may be made among these various terms, it is clear that all of them have reference to some portion of the ability to solve problems and think reflectively.

As early as 1928, Elliot Downing formulated a list of elements and safeguards of scientific thinking. There are seven elements on Downing's list: purposeful observation, analysis-synthesis, selective recall, hypothesis, verification by inference and experiment, reasoning, and judgment. Some of the 16 safeguards Downing lists are: "observation must be accurate; observation must be done under a variety of conditions; the essential elements in a problematic situation must be picked out; inferences must be tested experimentally; judgment must be passed on the pertinency of data" (pp. 231-232).

In subsequent years, other science educators added to the elements of scientific thinking on Downing's list or formulated new lists. Interesting contributions along this line were made by Keeslar (1945a, 1945b), Dunning (1949), Burmester (1952), Obourn (1956), and Novak (1961). More recently, some components of problem-solving ability, now in the guise of processes, were characterized by Welch (1966) and by the developers of the elementary-school curriculum, Science--A Process Approach (Livermore, 1964), and a taxonomy for processes of scientific inquiry was prepared by Klopfer (1971). There have been some other efforts to define component elements of problem-solving ability, but this brief overview describes the range of these efforts.

Despite the long-term efforts of science educators, a fully satisfactory definition of what problem-solving ability in science involves does not exist today. There is currently no single source, nor a simple combination of several sources, to which one can turn for a functional account of the behaviors, skills, or competencies that constitute the ability to solve problems. Can such an account of children's problem-solving ability be developed?

The historical experience suggests that the effort to devise a comprehensive compendium of all the component elements of problem-solving ability is likely to be futile. Another approach is needed to develop a clear, functional, and full definition of children's problem-solving ability in science. An approach that appears promising is based, in part, on carefully observing children of different ages who are competent problem solvers as they solve problems. From analyses of these good problem solvers' behaviors and the strategies they employ as they confront problems, it becomes possible to ascertain which skills and competencies related to problem solving children can be expected to attain at different ages or developmental stages. When these have been ascertained, they can be fitted into a framework of categories derived from the already available analyses of the processes of scientific inquiry that the science educators' historical efforts have provided. With problem-solving ability defined in this way, not only will the account of this desired outcome be sufficiently complete, but also the particular outcomes to be expected from children will be clear.

Children's attainment of problem-solving ability. As one surveys the science education literature of six decades that deals with problem solving, it is remarkable that the general outcome of developing children's problem-solving ability was never questioned. No one seems to have asked how reasonable it is to expect children on the average to attain this outcome. It is remarkable that this question was not raised, because one reality that every teacher recognizes is individual differences in children. Could it be, then, that there are no differences with respect to developing children's problem solving ability through science instruction? Hardly.

In connection with this issue, it is important to remember that the kind of intellectual behavior valued by Dewey and the science educators who followed him is not common. The science educators who attempted to add definition to the method of intelligence turned to the writings of a handful of the world's greatest scientist-philosophers. Although these lists were modified before being passed on to classroom teachers, one might expect that most teachers would be discouraged by the mere act of reading such an imposing list. Certainly, many teachers might wonder if they themselves possessed some of the subtle intellectual skills that were being described. Further, they might have grave doubts about their success in getting most children to engage in a kind of intellectual behavior that is characteristic of profound thinkers. And yet, developing problem-solving ability in science remained as a desired outcome for all children.

The main point is this: It is necessary to examine the question of the extent to which it is reasonable to expect all children to attain the outcome of developing their problem-solving ability. Perhaps this is not a popular question to ask in an egalitarian milieu, but it certainly seems educationally futile to hold up any goals for children that they cannot attain. We would suggest that the question be examined by means of empirical procedures, not by doctrinaire discussion. The observational studies suggested above, of children confronting problems, could be part of the experimental methodolgy. We do not know the details of what these investigations would reveal, but their main result would be a better match between the expected outcomes for different children in developing problem-solving ability and their individual capacities for attaining the outcomes.

More than 20 years ago, as part of a symposium on problem solving in science teaching, published in the February 1956 issue of The Science Teacher, Paul Dressel contributed a thoughtful article, titled "The Challenge." One of his observations then remains apt even today.

> Despite the interest manifested by many teachers in cultivating in their students what is variously called . . . critical thinking or problem solving, it is not surprising that actual accomplishment leaves much to be desired. The difficulties to be overcome are numerous and complex and the situation will not quickly be remedied. (p. 23).

Current Trends in Public Education

In view of the persistent issues described in the historical review about the definition of problem-solving ability and the delineation of problem-solving method and outcome, it is no wonder that problem-solving methods so frequently recommended by science educators are not often found in actual instructional practice in schools. With regard to the development of the ability to solve problems and to think reflectively, the evidence indicating that this desired outcome is being attained by students who have studied in schools is scanty. On the contrary, the results of the National Assessment in Science (1977), to take just one example, indicate that most students tested at ages 13 and 17 are deficient in just those higher-order mental skills (analysis, synthesis, evaluation) which are components of reflective thinking and problem-solving ability. Again, the outcome so frequently recommended by science educators is in practice not often realized as an actual outcome by students. As Harold Hodgkinson, former Director of the National Institute of Education, commented in 1977:

> If there is a common thread to the National Assessment data, it is in the complete failure of the schools to teach understanding, insight, and problem solving <u>in any subject area</u>. English teachers in college say that their students know the mechanics of reading, but they cannot read a four-page statement and construct a two-paragraph summary of the content. Math students know <u>how</u> to do subtraction and division, but they don't know when. (p. 11)

While current popular priorities in education stress going "back to basics," we ask: Of what value is the ability to add and subtract if the student cannot decide which of these operations to apply when confronted with a "word problem" in a math book or a practical problem outside the school? It is certain that, at the very least, some components of problem solving are basic to the education of all children. An essential task of educational research and development is to find ways of affording all children the opportunity to learn at least those basic problem-solving skills which are essential for their well-being in today's society.

Educational research and development should not ignore the educational needs of those children who are achieving competence in basic skills. One likely outcome of current discussions and curriculum changes will be an increase in the proportion of students whose mastery of the traditional basic skills is adequate. Given this outcome, it is unwise to limit the focus of research and development to only those problems in the practice of education that are identified as critical at a given moment. Research and development must meet the present crises, but also meet the needs of children who have achieved competence in basic reading and arithmetic skills.

Survival in our society requires skills beyond those defined by the so-called basics. There is no doubt that being able to budget one's money or to balance a checkbook are important and necessary computational skills. However, additional skills are needed. The average American must consider problems that require skills of formulating questions, finding relevant information, and reaching decisions. For example, faced with the alternative to make a single large expenditure to insulate one's home or to pay large monthly fuel bills, the homeowner must engage in much higher level thinking processes than simple computation to come to a rational decision. It is a responsibility of the schools to provide all children with the opportunity to learn basic thinking processes and information that they need to arrive at rational decisions in their day-to-day lives.

This line of reasoning points to the importance of developing children's problem-solving skills, not only through science education, but also wherever this can best be accomplished throughout the curriculum of the school. However, to the extent that past experience is a guide, it seems inevitable that a major share of the responsibility for accomplishing the problem-solving goal will continue to be lodged with science education. Our analysis of the history of problem solving in science education has suggested that, as a minimum, the problem-solving goal for science education should be the product of dual process. This process includes careful definition of problem-solving ability and empirical research on the extent to which individuals can be expected to learn the component skills of problem solving. Further definition of the goal must be a function of the immediate educational priorities of the nation, tempered by a vision of what education can be. There is no doubt that education can be much more than the acquisition of basic verbal and computational skills. It can, and indeed today it must, include the development of skills related to formulating and solving problems and making decisions. This very basic need for children to develop skills in certain components of problem-solving ability necessarily is a current concern in public education. Consequently, the need to emphasize problem solving as outcome and as method in science education is not likely to disappear in the foreseeable future.

Psychological Research on Problem Solving

Having examined the problem-solving goal in the light of considerations suggested in our first recommendation, we turn in this section to the bearing of cognitive psychological research on the problem-solving goal in science education. The framework for the discussion in the following section is our second recommendation that science educators should take the responsibility for translating research methods, findings, and theories of behavioral scientists into research and instructional procedures in science education. In this section, we adhere to our second recommendation with respect to science education research and instruction in problem solving and attend to the many valuable contributions which can be derived from the research and theories of psychologists who study learning. Before taking up that discussion, however, we must place in perspective the particular contributions of psychology to the extensive domain of problem solving in education.

Problem solving is a ubiquitous and complex human behavior that is one focus of inquiry in all the disciplines that are seeking a better understanding of human behavior. There is, therefore, extensive scholarly literature on human problem solving. Represented within this literature are perspectives on human problem solving that reflect various philosophical persuasions and the diverse reference frames of the many behavioral and social sciences. The goal of each of the behavioral and social sciences is to better understand that facet of human problem solving that is most relevant to that science's interest. The perspective on problem solving of education is quite different from that of science. A goal of education is to teach people to be creative problem solvers. If this goal is to be achieved through students' school experiences, educators must take cognizance of both the broad range of problems that confront their students and the multiplicity of philosophical and scientific perspectives that can guide the analysis of human problem solving. Education's perspective is broad, integrative, and pragmatic--a perspective that contrasts sharply with the more narrow, analytical, and theoretical perspective of the scientist. This difference in perspective is one factor that makes the task of applying the knowledge generated by science to educational practice a formidable one.

Educators seeking to improve educational practice often turn to the research of psychologists. Our own work is an example of this generalization. We believe that the cognitive psycholog :al perspective on problem solving is a necessary one for science educators to understand. However, this perspective alone is not sufficient. For example, cognitive psychological studies rarely, if ever, consider the influence of personality traits, culture, or the sociology of the classroom on students' development of problem-solving skills. The educator cannot afford such a restricted view. Even if the application of cognitive psychological theory to instruction is a primary goal of an educator, the educator also must take many other factors into consideration.

Only the intrepid educator will persist long in the task of applying psychological theory to instructional practice. The first impression obtained by an educator sampling the problem-solving literature of psychology is that it is an area in chaos. That impression is not dispelled by better acquaintance. A 1966 review of the area by Gary Davis (1966), a psychologist, begins with these words: "Research in human problem solving has a well-earned reputation for being the most chaotic of all identifiable categories of human learning" (p. 36). In a similar vein, James Greeno (1978) comments in a discussion of the literature on the experimental psychology of problem solving that "recent analyses of problem solving have dealt substantively with the psychological nature of problem solving, in ways that contrast sharply with the vague and superficial discussions that characterized behaviorists' work on the topic" (p. 240).

There are as many different perspectives on the psychology of problem solving as there are schools of psychology. Each of the various perspectives develops some understanding of some aspects of problem solving, but none has as yet illuminated the whole domain. (We recall, in this connection, the parable of the blind men studying the elephant.) Nevertheless, the contributions of any particular psychological perspective on problem solving to education research and practice can be very valuable, as long as one has no delusions about the limits of the selected perspective. We have ourselves found several perspectives of cognitive psychologists on problem solving to be wellsprings for research and instructional procedures relating to problem solving in science education. However, the cognitive psychological theories and research findings generally appear in the research literature in a form that is not directly usable, so that translations are necessary. In the implementation of our second recommendation that follows, we first consider the translation of research into instructional procedures for problem solving, and then we turn to the translation of psychological theory and research into science education research procedures.

Translation into Instructional Procedures

The process of translating psychological theories and research findings into instructional procedures for science education is challenging and complex. Nonetheless, undertaking the challenge to effect the necessary translation is worthwhile because instructional procedures which have been conscientiously designed on a sound psychological basis are more likely to be successful in having students achieve cognitive objectives than those which have not. One of our recent research activities involves the design of an instructional module about area for upper-elementary school children. We think that the specific example of the area module provides a good context for discussing the translation of psychological theories and research findings into instructional procedures.

Our choice of the concept of area for our instructional module was guided by several considerations. First, there has been a considerable amount of psychological research on the concept of area, and some of this could be brought to bear in designing the module. Second, area is a basic concept in mathematics and science, and it is used frequently in various other academic subjects as well. In geography, for example, the concept of area is needed in calculating the amount of arable land a country has to feed its people. In biology, knowing the surface area an animal has for oxygen-carbon dioxide exchange helps to determine its activity level. In physics, the pressure is the force exerted on a unit area. Third, the concept of area has many practical applications in people's daily lives. How much cloth is needed to make a skirt, how much linoleum to cover the kitchen floor, how much grass seed to sow the lawn, how much paint for the bathroom walls? All these are questions or problems that most people confront at one time or another. Finally, despite the considerable attention given to teaching area, many upper-elementary children experience difficulty in acquiring an understanding of the concept, and so we hoped to devise an effective instructional procedure to help them understand area. To do so, we took into consideration four psychological perspectives as represented primarily in the work of five psychologists: Edward Thorndike, a classical associationist; Max Wertheimer, a Gestalt psychologist; Jean Piaget, a structuralist; and Lauren Resnick and Robert Glaser, representing the information-processing perspective.

Associationist and Gestalt perspectives. The perspective of Edward Thorndike, an associationist, is an important one because he influenced two salient aspects of current classroom practice, namely, the importance of drill and the value placed on a student's ability to recall information quickly. Thorndike's theoretical position (1921, 1922) is that problem solving, like other kinds of thinking, results when we mentally combine or associate ideas or concepts that contain one or more common elements. This viewpoint has led to instructional procedures that rely on frequent practice or drill to strengthen desirable associations between concepts. The notion behind these procedures is that if students practice recalling information quickly and accurately, they are then able to use this information when presented with a problem to solve.

Because of the influence of Thorndike and other associationists, children in most American schools are taught about area by an instructional approach that is a direct application of classical associationist theory. They memorize a formula, learn how to substitute numbers into the formula, and carry out the necessary arithmetical calculations. This approach is usually highly effective in enabling children to solve problems where the task is simply to apply an algorithm, or standard method, to the problem situation. For example, the formula for finding the area of a rectangle is Area = length x width. A typical problem which the student solves by applying the substitution algorithm is: A rectangle is 5 cm long and 3 cm wide; what is the area of the rectangle? Practice with problems like this constitutes most of the students' wo. . in the algorithmic approach to teaching area. One of the inadequacies of this approach is that, after being instructed only in the use of a particular algorithm, very few students are able to solve problems where they cannot immediately apply the algorithm. For example, after receiving instruction in only the substitution algorithm for finding the area of a rectangle, few students can solve this problem: One side of a parallelogram is 7 cm long and another side is 5 cm long; what is the area of the parallelogram? This is the classic area-of-a-parallelogram problem which has figured prominently in the research of cognitive psychologists for many years. We have made use of some findings of this research in designing the area module.

Max Wertheimer was a Gestalt psychologist who believed that Thorndike's ideas about teaching children how to solve problems were wrong. Wertheimer was convinced that the associationist methods fostered "ugly thinking" and a trial-and-error approach to problems, because the emphasis was on memorizing formulas and practicing mechanical substitutions. He argued that concepts should be taught by means of problems that give students a "structural understanding" of the principles involved (Wertheimer, 1945/1959; Luchins & Luchins, 1970). Wertheimer carried out numerous studies in which he presented people with challenging problems that embodied mathematical and geometrical concepts. He analyzed people's approaches to these problems in terms of whether his subjects showed evidence of understanding the underlying concepts or whether they attacked these problems by trial and error. He found that persons whose knowledge of a concept was based on memorized associations were often unable to solve problems presented in nonstandard ways and often approached problems in a way that showed they did not understand the underlying principles. On the other hand, persons who learned concepts through understanding rather than drill were able to deal successfully with problems by using "productive thinking" (Wertheimer's term for problem solving).

Wertheimer's proposed method for teaching children the concept of area contrasts greatly with the associationist method of memorizing a formula and substituting numbers into it. He argued that the proper "structural understanding" of area measurement could be developed in students by showing them how to use unit squares to cover an object whose area was to be measured. Children who first learned to measure area in this fashion, according to Wertheimer, would eventually develop a conceptual understanding of the formulas for area measurement. Having this understanding, they would realize, for instance, that multiplying the length of a rectangle by its width gives the same numerical answer as multiplying the number of unit squares in one row by the total number of rows. After children came to understand how to measure the area of a rectangle using unit squares, they would then be given other figures to measure on which the unit squares would not fit evenly. Giving students these opportunities to invent new procedures for measuring area would help them increase their understanding of area measurement and would also help them develop strategies for solving problems. Wertheimer was particularly interested in how people who knew how to find the area of a rectangle applied this knowledge when asked to find the area of a parallelogram. One feature in our area module that is adapted from Wertheimer's research is teaching children how to use unit squares to measure area. We also have used some of his ideas about problem solving in choosing a sequence of problems to interweave with the instructional lessons of the module. Wertheimer's ideas suggest that students' early academic experiences with solving problems should include at least two types of problems: problems that allow students to apply methods they have already learned and problems for which students have not learned a standard method of solution. As the content overview of the area module in Table 1 indicates, each part of the module includes problem-solving experiences of both types.

Gestalt psychology is both a reaction to associationism and one of the psychological perspectives that introduced the notion of structure to psychology. While the Gestalt view of structure differs from that of the structuralists, the notion of wholeness is central to both schools of thought. In the theory of Jean Piaget, to whom we turn next, the notion of wholeness is central to the characterization of the logico-mathematical mental structures.

<u>Structuralist perspective</u>. For nearly half a century, the Swiss genetic-epistemologist, Jean Piaget, has engaged in research to broaden the scientists' understanding of the question, "How does knowledge develop?" To answer this question, Piaget has studied the development in humans of the ability to reason and to think logically. Piaget assesses an individual's ability to reason by presenting the individual with problems to solve. Piaget and his co-workers have confronted hundreds of children with many problems drawn from science and mathematics. The responses children give to the problems and the reasons they give for their responses are carefully analyzed to determine the underlying structure of their thought processes. To the extent that a child's answers seem to follow a logical pattern, Piaget assumes a certain organization of mental processes. Hence, the Piagetian problems serve as probes into the mental processes behind children's reasoning ability.

Among the problems Piaget and his colleagues have used are various problems about area (1960, 1967). They have developed a series of problems that can be used to probe children's mental processes and to define in terms of behavior what is meant by the phrase, "understand the concept of area." The first problem in the area series probes the child's understanding of an axiom from Euclidian geometry: If equals

Table 1

Content Overview of the Area Module

Lessons	Skills and Content Taught	Associated Problems
Part I. Length	Ordering line segments and sticks by length; measuring lengths of line segments in inches.	
	Practice Sheet I. Length: Comparing lengths of line segments, ordering line segments by length, measuring line segments and distances between points in inches.	
Part II. Squares and Rectangles	Identifying properties of squares and rectangles; identifying right angles, squares, and rectangles; inclusion of the class squares in the class rectangles; identifying and measuring the length and width of rectangles.	Using four lines of equal length to construct an object with four right angles that is not a square.
	Practice Sheet II. Squares and Rectangles: Identifying right angles.	Constructing four-sided objects with specified lengths of sides, kinds of angles, etc.
Part III. Comparing Areas	Observing that congruent rectangles have equal areas and that rectangles equal in one dimension, but unequal in the other, have different areas.	Determining how many squares will cover a rectangle that is congruent to another rectangle that can be covered by a known number of squares.
Part IV Measuring Area	Measuring area of a rectangle by constructing a congruent rectangle from unit squares, then counting the squares.	Comparing the relative areas of two rectangles of different shape, one of which has been transformed from a figure congruent to the first rectangle (area conservation). Inventing a method of measuring the area of a narrow rectangle whose width is one-half that of a unit square.
	Practice Sheet IV. Measuring Area: Measuring the areas of rectangles using unit squares.	Inventing a method of measuring the area of a triangle, given that scissors may be used.
Part V Shape and Area	Comparing areas of rectangles of different shapes whose parts can be rearranged to form congruent rectangles (area conservation). Measuring the area of these rectangles with unit squares	
	Practice Sheet V. Shape and Area (A): Measuring the area of a figure using unit squares before and after transforming its shape. Comparing the areas of the original figure with that of the transformed figure.	
	Practice Sheet V. Shape and Area (B): Measuring the areas of triangles, trapezoids, and other figures by transforming them into rectangles on which congruent figures can be constructed from unit squares.	Inventing a method of measuring the area of a parallelogram.

are subtracted from equals, the results are equal. A second set of problems tests the child's understanding of the fact that, under certain conditions, the shape of an object can be transformed while its area remains the same. This is an important concept for solving the parallelogram problem--i.e., that there is a way of transforming a parallelogram into a rectangle so that the area of the rectangle is the same as the area of the parallelogram. A third set of problems probes the child's understanding of the principles underlying the measurement of area. The child is asked to compare the areas of two figures by superposition, which involves placing one figure on top of another and noting any overlap. The child's conceptualization of a unit of area measurement is probed by having the child measure the area of an object by covering it with unit squares and counting the squares. Then the child is asked to measure the area of a plane figure using a single unit square. Since only a single unit square is available, the child must make several successive placements of that unit square, coordinating each placement in space so that there is no overlap or gap. To carry out this process successfully, the child must impose some mental organization on the surface of the figure, e.g., visualizing it as a grid composed of identical squares. This implies a certain degree of structure in the child's mental processes.

Each of the Piagetian tasks or problems we have described here highlights some mental process involved in a child's understanding of the area concept. According to Piaget, the mental operations necessary for understanding the concept of area are analogous to and derive from the physical manipulations the child carries out with objects. By extension, providing children with concrete experiences such as Piaget describes may help them develop the mental processes needed to understand area. The area module we designed includes manipulative experiences--Piagetian-type area problems that the child "solves" by using manipulative materials. The inclusion of these experiences is consistent both with Piagetian theory and certain aspects of Gestalt psychology.

Information processing perspective. Another important line of research on problem solving has come from a group of cognitive psychologists who view problem solving as information processing (Ernst & Newell, 1969; Newell & Simon, 1972). Information processing psychology is based on the assumption that human beings' mental processes may be productively compared to the operations of computers. The notion behind this view is that human beings, like computers, both store and process information. The series of operating instructions which make up a computer program, and which are stored in the computer's "memory," are seen as analogous to human mental processes which are stored in human memory. Once programmed, the computer can take in information relevant to a specific problem, process the information through the operating instructions of the program, and output a solution to the problem. Similarly, human beings take in information from a problem-solving task, manipulate that information in their minds, and come up with a problem solution.

To learn more about how humans think, information processing psychologists try to program computers to solve certain types of problems in the way a human being would. First they carefully observe the steps humans use to solve a particular problem. Then each of the steps a human problem solver uses becomes an operating instruction in the computer program. Writing a computer program helps the psychologist conceptualize and specify the kinds of decisions and the sequence of decisions that humans make in solving particular kinds of problems. The sequence of decisions can be outlined in schematic diagram, an example of which is shown in Figure 1. Taken from the work of Lauren Resnick and Robert Glaser (1976), this diagram outlines the sequence of decisions used in solving certain types of mathematical problems.

Resnick and Glaser's general scheme is applicable to several interesting types of problems--for example, the problem of finding the area of a parallelogram. The analysis scheme helps to make clear how having

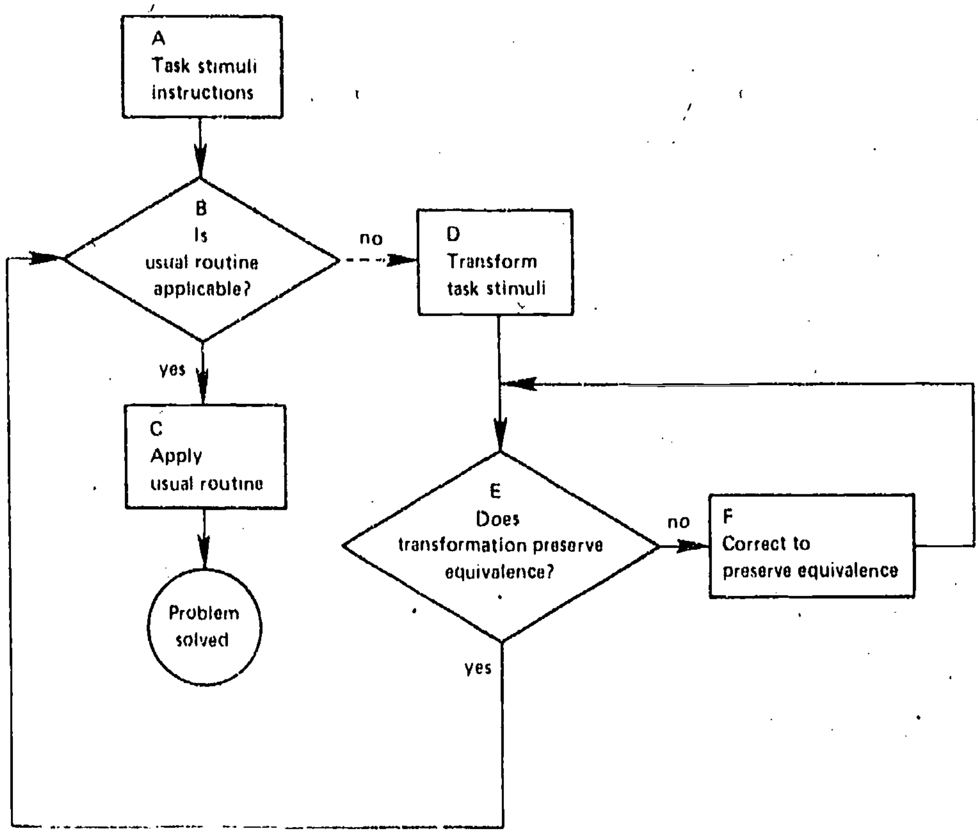

Figure 1 Schematic diagram of successful problem solving. (From "Problem Solving and Intelligence" by Lauren B Resnick and Robert Glaser, in L.B. Resnick (Ed.), *The Nature of Intelligence,* Hillsdale, NJ. Lawrence Erlbaum Associates, 1976.)

a real understanding of the area of a rectangle makes it possible for a child to solve the area-of-a-parallelogram problem. By utilizing the general scheme to analyze this problem, a schematic diagram is obtained in which each rectangle and diamond shows where some particular kind of mental processing takes place. By following along the arrows in the diagram, we can trace the steps by which the area-of-a-parallelogram problem is solved. Even such a gross analysis of the mental processes involved in a problem solution provides an insight into how people solve problems in general. It also suggests some ways that we might plan a sequence of instruction to facilitate problem solving.

In designing the sequence of instruction for the area module, we began with Resnick and Glaser's information processing analysis of problem solving as a basic outline. We modified some of the steps of the analysis where tests with children (using instruction based on that outline) had suggested the analysis was incomplete, and we added some instructional activities based on Piaget's work, which we have already described. The complete sequence of instruction in the area module is shown in Table 1 (page 22). The module first teaches the child to recognize the attributes of rectangles, figures whose areas he or she will later learn to measure. Next, the child's conception of area is developed through the exercise of comparing objects with different areas, and the methods of measuring area by using unit squares is taught. Then the child is taught how to transform the shapes of objects and how to compare their area before and after they have been transformed (area conservation). Finally, the student learns some ways to transform nonrectangular objects into rectangles so that their area can be measured using the unit squares. In summary, the area module is designed to provide the skills and information needed so that a student can make the appropriate decision at each step of the schematic outline for solving the area-of-a-parallelogram problem.

Our brief description of the ways in which we incorporated the four different psychological perspectives into our instructional module serves to illustrate the general points we made at the beginning of this section of the paper. Specifically, we have illustrated that the rather focused view of problem solving taken by the psychologists of a particular school of psychology is not sufficient for dealing with the multiple aspects in the design of instruction. Thus, it becomes necessary for the educator to analyze each psychological theory, determine to which aspects of instruction the theory applies, and then translate the theory into instruction.

Translation into Science Education Research Procedures

As the preceding discussion has indicated, translating contributions of psychological theory and research into instructional procedures for problem solving is quite challenging and complex. Somewhat more straightforward but no less challenging, in our opinion, is effecting translations of psychological theory and research methodology into science education research procedures. One case in point is offered by the theoretical and methodological contributions of Jean Piaget, a part of whose work we have already discussed above. Applications of Piaget's theories and translations of his methodology in science education research have been made by a number of investigators; see, for example, the Piaget-based studies reviewed in Mallinson (1977, pp. 10-20). Moreover, Piagetian theory and methodology are specifically applicable to research pertaining to problem solving.

The developmental theory of Piaget delineates the mental operations that are necessary for the solution of formal (academic) problems and the mental operations that children can be expected to attain at various ages. Thus, Piagetian theory provides one standard against which the attainability of the problem-solving goal can be judged. This means that research applying Piagetian theory could fill the great gap in existing knowledge (that we identified earlier in this paper) about the extent to which it is reasonable to expect average children at different ages to attain the problem-solving goal of science education. In addition, Piaget's clinical interview method suggests a potentially valuable research methodology for empirically determining the extent to which factors other than the possession of specific logico-mathematical operations affect a child's ability to solve problems. In this application, we see a promising methodology for going beyond the strictly cognitive considerations to the investigation of other important influences contributing to successful problem solving in science classrooms.

To illustrate further the translating and application of psychological research methods in research pertaining to problem solving in science education, we shall cite some examples from our own research. We have found the research methods of cognitive psychology to be a rich source of ideas for our research. The purpose of this research is to explore the relationships among (a) problem solving ability, (b) knowledge structures, and (c) the structures of the natural science disciplines. We also expect to apply the results of this research to the improvement of instruction for problem solving (Champagne & Klopfer, 1977). An important instrument in our conduct of this research is the Concept Structuring Analysis Technique (ConSAT). The inspiration for this technique came from the research of two congitive psychologists, Paul Johnson (1964) and Richard Shavelson (1974). Both of these investigators sought ways of determining how individuals relate science concepts in memory. Our ConSAT is an extension of the card-sort technique, a method which Shavelson used to investigate this question.

In our research using the ConSAT, each concept structuring task is administered on an individual basis in the following manner. After introductions and small talk, the researcher tells the student, "We are trying to find out how students think about words used by scientists." The researcher hands the student a stack of cards and asks the student to read the words on the cards and to sort them into two stacks. One stack of words is those the student recognizes (has seen or heard before). Words that the student does not recognize go into the other stack. The researcher then asks the student to arrange the recognized words on a large piece of paper in a way that "shows how you think about the words." While completing the arrangement, or after its completion, the student is asked to tell why the words are arranged as they are. As the student points out relationships between the words, the researcher connects the related words or groups of words with a line and then labels the line with the relationship which the student gives. The researcher also asks questions about the arrangement of words on the paper when the student does not volunteer information. The students often change a card from one position to another. The researcher encourages this and asks questions about the change, while noting the change and other relationships. Finally, the student is asked to go through the stack of unrecognized words and make a final attempt to fit them into the structure already produced. In Figure 2, taken from one of our studies (Champagne, Klopfer, DeSena & Squires, in press) using the ConSAT, we show the arrangement of a group of geological terms and the relationships between them that was generated by a student to whom we presented the structuring task.

When the ConSAT is used as a pre- and postinstruction task, we note changes in the arrangements produced by the students. The postinstruction arrangements are more structured than the preinstructional arrangements, and the structural characteristics of the postinstructional arrangements have congruence with the science discipline structure as it is represented in the instructional materials (Champagne, Klopfer, DeSena & Squires, 1978). Assuming that a composite knowledge structure of experts in the field of geology is essentially congruent

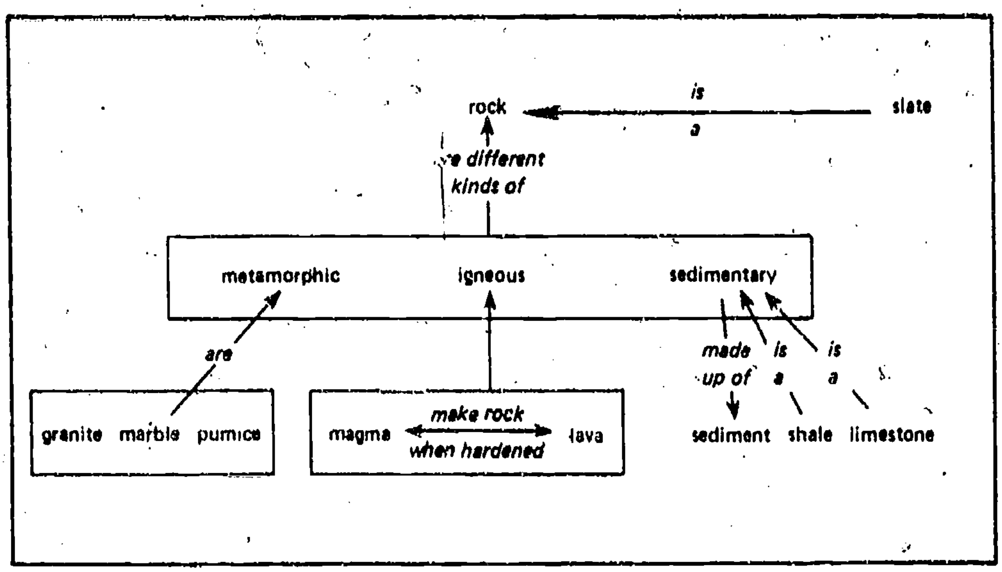

Figure 2. Pre-instructional ROCK structure for student 18.

with the discipline structure of geology, we generated a composite "expert" structure that has all the essential characteristics of the discipline structure (which is represented in the instructional materials). This "expert" structure is the standard against which student arrangements are compared.

While psychological research using card-sort techniques relies on quantitative methods of data analysis, we have elected to use a qualitative method for the analysis of student structures. It is our opinion that much of the richness of the students' knowledge structures is lost in the quantitative analyses. Subtle differences in representations can be detected by the qualitative analytical procedures we apply to the representations. Although conciseness is a definite characteristic of a quantitative analysis of the data and the quantitative analyses also have the potential advantage of making possible rather rigorous statistical comparisons of structures between groups or between individuals, the conciseness and rigor are more than offset, we believe, by what is lost in the reduction of the representations to numbers.

The development of the ConSAT for use in our research is an example of the subtle translation of a concise, mathematically rigorous technique for scientifically probing knowledge structures into a richer, descriptively rigorous technique for assessing changes in students' knowledge structures as a result of instruction. The changes made in the technique to meet the goals of educational, rather than psychological, research are significant and serve to illustrate some of our earlier remarks concerning the need for translations. Having made the translation and produced the ConSAT, we utilized this technique to explore the relationships between students' knowledge structures of science concepts and other factors of interest in the investigation of problem solving. In one such study, we considered the relationship between the students' knowledge structures of certain geological concepts and their success in solving academic problems involving the same concepts (Champagne et al. 1978). As our problem-solving research program proceeds, we plan to take advantage of every sensible opportunity for translating psychological theory and research methodology into usable science education research procedures.

Conclusion

This paper has proposed two recommendations that investigators might well follow if they wish to reorient science education research. We have refrained from arguing for these recommendations for reorientation on theoretical grounds, but instead have been pragmatic and illustrated the applicability of our two recommendations as operating principles to research on problem solving in science education. By doing so, we have been able to call attention to some significant details concerning the adherence to the recommendations to real, ongoing research.

Although in this paper we apply our recommendations to only one research area, we believe that they may be profitably utilized in other areas of research interest in science education. If that is correct, the broader applications of the two recommendations as operating principles could make a genuine difference in the orientation and productivity of science education research.

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